Moments of the neutron g_2 structure function at intermediate Q^2

P. Solvignon[23,1,13], N. Liyanage[24], J.-P. Chen[13], Seonho Choi[21,23], K. Slifer[23], K. Aniol[3], T. Averett[25], W. Boeglin[8], A. Camsonne[2], G. D. Cates[24], C. C. Chang[16], E. Chudakov[13], B. Craver[24], F. Cusanno[10], A. Deur[24], D. Dutta[5], R. Ent[13], R. Feuerbach[13], S. Frullani[10], H. Gao[5], F. Garibaldi[10], R. Gilman[13,20], C. Glashausser[20], V. Gorbenko[12], O. Hansen[13], D. W. Higinbotham[13], H. Ibrahim[19,4], X. Jiang[20], M. Jones[13], A. Kelleher[25], J. Kelly[16†], C. Keppel[9,13], W. Kim[15], W. Korsch[14], K. Kramer[25], G. Kumbartzki[19], J. J. LeRose[13], R. Lindgren[24], B. Ma[18], D. J. Margaziotis[3], P. Markowitz[8], K. McCormick[19], Z.-E. Meziani[23], R. Michaels[13], B. Moffit[25], P. Monaghan[18], C. Munoz Camacho[6], K. Paschke[17], B. Reitz[13], A. Saha[13†], R. Shneor[22], J. Singh[24], V. Sulkosky[25], A. Tobias[24], G. M. Urciuoli[11], K. Wang[24], K. Wijesooriya[5], B. Wojtsekhowski[13], S. Woo[15], J.-C. Yang[7], X. Zheng[1], L. Zhu[18]

(Jefferson Lab E01-012 Collaboration)

[1] *Argonne National Laboratory, Argonne, IL 60439*

[2] *Université Blaise Pascal et CNRS/IN2P3 LPC, 63177 Aubière Cedex, France*

[3] *California State University, Los Angeles, Los Angeles, CA 90032*

[4] *Cairo University, Giza 12613, Egypt*

[5] *Duke University, Durham, NC 27708*

[6] *CEA Saclay, DAPNIA/SPhN, F-91191 Gif sur Yvette, France*

[7] *Chungnam National University, Taejon 305-764, Korea*

[8] *Florida International University, Miami, FL 33199*

[9] *Hampton University, Hampton, Virginia 23668*

[10] *Istituto Nazionale di Fisica Nucleare, Gruppo Collegato Sanitá, Seziona di Roma, 00161 Roma, Italy*

[11] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 00185 Roma, Italy*

[12] *Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine*

† Deceased

[13] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606*
[14] *University of Kentucky, Lexington, KY 40506*
[15] *Kyungpook National University, Taegu City, Korea*
[16] *University of Maryland, College Park, MD 20742*
[17] *University of Massachusetts, Amherst, MA 01003*
[18] *Massachusetts Institute of Technology, Cambridge, MA 02139*
[19] *Old Dominion University, Norfolk, VA 23529*
[20] *Rutgers, The State University of New Jersey, Piscataway, NJ 08855*
[21] *Seoul National University, Seoul, 151-747, Korea*
[22] *University of Tel Aviv, Tel Aviv, 69978 Israel*
[23] *Temple University, Philadelphia, PA 19122*
[24] *University of Virginia, Charlottesville, VA 22904*
[25] *College of William and Mary, Williamsburg, VA 23187*

(Dated: April 17, 2013)

Abstract

We present new experimental results of the ^{3}He spin structure function g_2 in the resonance region at Q^2 values between 1.2 and 3.0 (GeV/c)^2. Spin dependent moments of the neutron were then extracted. The resonance contribution to the neutron d_2 matrix element was found to be small at $\langle Q^2 \rangle$=2.4 (GeV/c)^2 and in agreement with the Lattice QCD calculation. The Burkhardt-Cottingham sum rule for neutron was tested with the measured data and using the Wandzura-Wilczek relation for the low x unmeasured region. A small deviation was observed at Q^2 values between 0.5 and 1.2 (GeV/c)^2 for the neutron.

PACS numbers: 13.60.Hb, 13.88.+e, 14.20.Dh

The measurements of nucleon spin structure functions in polarized Deep Inelastic Scattering (DIS) have been instrumental in advancing our understanding of Quantum Chromo-Dynamics (QCD) (for a recent review of nucleon spin structure measurements, see [1, 2]). Most of these experiments were performed using nucleon targets polarized longitudinally with respect to the lepton spin. In this case the helicity dependent cross section difference is dominated by the g_1 spin structure function, and as a result, this structure function is known with high precision in most kinematic regions. In the naive Quark Parton Model (QPM), g_1 is directly related to the polarized quark distribution functions inside the nucleon. In the limit where the four-momentum transfer squared, $-Q^2$, is very large, the lepton-nucleon scattering can be well described by a non-interacting, pointlike quark with a momentum fraction $x = Q^2/(2M\nu)$ of the parent nucleon's momentum (M is the mass of the nucleon and ν is the energy transferred). The contributions from electron scattering off these asymptotically free quarks to the structure functions are independent of Q^2, up to corrections due to gluon radiation and vacuum polarization. At high Q^2 these corrections can be accurately calculated using perturbative QCD. As Q^2 decreases, quark-gluon and quark-quark correlations make increasingly important contributions to the structure functions. In the g_1 structure function these correlation terms are suppressed by factors of $(1/Q)^n$ with respect to the asymptotically free contributions. In the case of the second spin structure function, g_2, the non-perturbative multi-parton correlation effects contribute at the same order in Q^2 as asymptotically free effects.

The moments of structure functions provide especially powerful tools to study fundamental properties of the nucleon, because they can be compared to rigorous theoretical results like sum rules and lattice QCD calculations. The Operator Product Expansion (OPE) of QCD [3, 4] can be used to relate the hadronic matrix elements of current operators to the moments of structure functions. In the OPE, the moments are expanded in a series ordered by $1/Q^{\tau-2}$. In this expansion $\tau = 2, 3, 4....$ is known as the twist (dimension - spin) of the operator. The twist-2 contributions to the moments correspond to scattering off asymptotically free quarks, where the higher twist contributions arise due to multi-parton correlations.

The Cornwall-Norton (CN) moments of g_1 and g_2 are defined by the equation:

$$\Gamma_{1,2}^{(n)}(Q^2) \equiv \int_0^1 dx\ x^{(n-1)}\ g_{1,2}(x, Q^2), \tag{1}$$

At high Q^2, the twist-3 reduced matrix element d_2 can be related to the second moment of

a certain combination of g_1 and g_2:

$$d_2(Q^2) = \int_0^1 dx\ x^2\ \left[2g_1(x,Q^2) - 3g_2(x,Q^2)\right]$$
$$= 3\int_0^1 dx\ x^2\ \left[g_2(x,Q^2) - g_2^{WW}(x,Q^2)\right] \quad (2)$$

Furthermore, the leading order contributions to g_2 can be calculated using measured values of g_1 in the Wandzura-Wilczek relation,

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(y,Q^2) \quad (3)$$

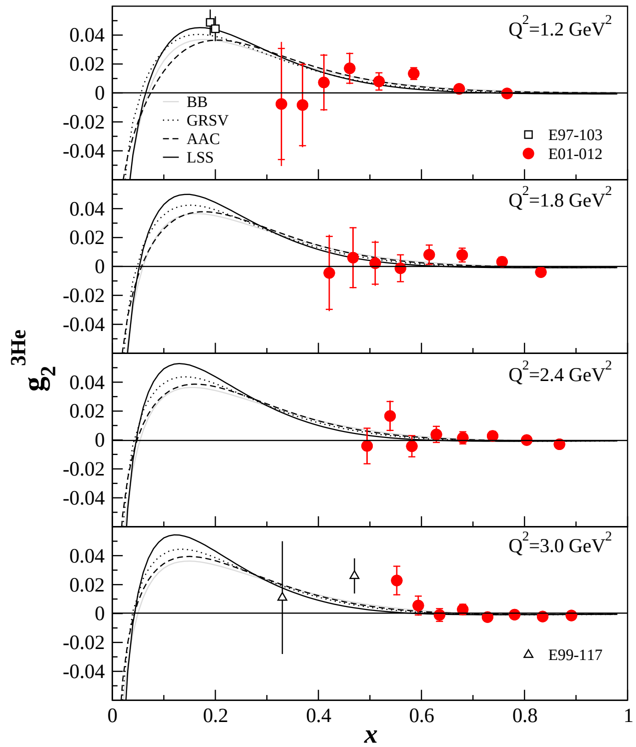
Hence it is possible to cleanly isolate the twist-3 contribution in a measurement of g_2 by subtracting the leading twist part. This makes the g_2 structure function ideal for the study of quark-gluon correlations.

The measurement of g_2 requires a polarized nucleon target with its spin direction transverse to the electron spin; in this case g_2 dominates the helicity dependent cross section difference. Due to technical difficulties associated with transversely polarized targets, precision data for g_2 are still lacking in many kinematic regions.

In the present paper, we report results of the neutron partial moments over the resonance region at Q^2-values of 1.2, 1.8, 2.4 and 3.0 (GeV/c)^2 from Jefferson Lab (JLab) Hall A experiment E01-012. These moments were evaluated with the g_2 structure function measured in the nucleon resonance region using a polarized ^{3}He target as an effective polarized neutron target. We formed polarized cross-section differences from inclusive scattering of longitudinally polarized electrons off a longitudinally or transversely polarized ^{3}He target. The extraction of g_2 from the polarized cross section differences was done following the formula:

$$g_2 = \frac{MQ^2\nu^2}{4\alpha_e^2}\frac{1}{2E'}\frac{1}{E+E'}\left[-\Delta\sigma_\parallel + \frac{E+E'\cos\theta}{E'\sin\theta}\ \Delta\sigma_\perp\right] \quad (4)$$

where $\Delta\sigma_\parallel$ and $\Delta\sigma_\perp$ are polarized cross section differences corresponding to longitudinal and transverse target polarizations respectively. The structure function $g_2^{^3\mathrm{He}}$ was extracted at constant beam energies and scattering angles. However, the integrations to form moments require the structure function values at a constant Q^2. Therefore our $g_2^{^3\mathrm{He}}$ results were interpolated to extract $g_2^{^3\mathrm{He}}$ values at four constant Q^2-values of 1.2, 1.8, 2.4 and 3.0 (GeV/c)^2. The results from $g_1^{^3\mathrm{He}}$ were reported in a previous publication [11] along with the details of the experimental setup. Figure 1 presents the results on $g_2^{^3\mathrm{He}}$ from E01-012 at the four Q^2



[t]

FIG. 1: (color online). The spin-structure function $g_2^{^3\text{He}}$ (per nucleon) in the resonance region at Q^2-values of 1.2, 1.8, 2.4 and 3.0 (GeV/c)^2. The error bars represent the total uncertainties with the inner part being statistical only. Also plotted are the DIS JLab data from experiments E97-103 [5] and E99-117 [6] (note that these data are at different Q^2). The curves were generated from the NLO parton distribution functions of Refs. [7–10].

values. Also plotted are the NLO parton distribution functions of Refs. [7–10] generated using Eq. 3, including target mass corrections (TMCs) from the formalism of Ref. [12].

The $g_2^{^3\text{He}}$ results at the four Q^2 values were used to evaluate the partial moment $\overline{d}_2(Q^2)$ over the resonance region for ^{3}He. Then $\overline{d}_2(Q^2)$ for the neutron was extracted from $\overline{d}_2^{^3\text{He}}(Q^2)$ using the method described in Ref. [13]:

$$\overline{d}_2^n = \frac{1}{p_n}\overline{d}_2^{^3\text{He}} - 2\frac{p_p}{p_n}\overline{d}_2^p \tag{5}$$

where p_n and p_p correspond to the effective polarization of the neutron and proton inside ^{3}He [14]. Data for the proton spin structure function g_1^p from JLab experiment EG1b [15] were used to calculate $g_2^{WW,p}$ and perform the neutron extraction.

From the four Q^2 values, we obtained the weighted averaged value of $\overline{d}_2 = 0.0002 \pm 0.0004 \pm 0.0009$ at $\langle Q^2\rangle$=2.4 (GeV/c)^2 and is shown on Fig. 2. Also shown are the earlier

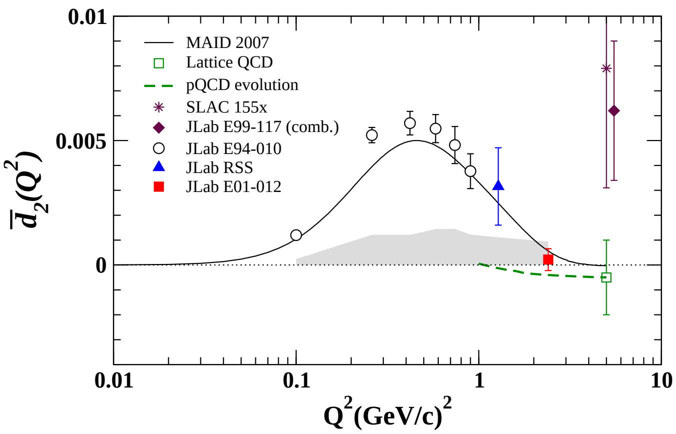


FIG. 2: (color online). Results on the *resonance contribution* to the neutron x^2-weighted moment $\overline{d}_2(Q^2)$ from E01-012. The error bars are statistical only and the band represents the experimental systematic errors. Data from JLab experiments E94-010 [16] and RSS [17] are shown. For comparison to the resonance contribution, we plotted the MAID model [18]. Also plotted are the *total* d_2 from SLAC E155x [19] and the *total* d_2 from SLAC E155x and JLab E99-117 [6] combined. The Lattice QCD prediction [20] was evolved down to our Q^2 value following the formalism of Ref. [21].

results from JLab experiments E94-010 [16] and RSS [17]. It can be seen that these three sets of data are in very good agreement with the MAID model [18]. Since $d_2(Q^2)$ is weighted by x^2, one would expect it to be dominated by the contribution coming from the resonance region, which sits at higher x compared to the DIS region. However our data show the resonance contribution to $d_2(Q^2)$ becoming very small by $Q^2 = 2$ (GeV/c)^2 as does the MAID model. The SLAC experiment E155x [19] evaluated $d_2(Q^2)$ including both DIS and resonance region data at $Q^2 = 5$ (GeV/c)^2. Their result for $d_2(Q^2)$ was large and positive, although with a large statistical uncertainty. However the $d_2(Q^2)$ integration should be performed over the entire x range but at fixed Q^2. The SLAC E155x extracted their value of $d_2(Q^2)$ from data over a wide range in Q^2, i.e. from 0.8 to 18.4 (GeV/c)^2. This could have masked some Q^2 dependence effects from the large resonance contibution at low Q^2, as can be seen on Fig. 2. The uncertainty has been improved by about a factor of 2 with the addition of the more recent measurement from JLab E99-117 [6], and is less than 2σ away from the Lattice QCD prediction [22]. Finally, the Lattice QCD prediction was evolved down to the Q^2 value of E01-012 using the formalism of Ref. [21]. The good agreement between the theoretical prediction and our data point suggests that the DIS contribution

to $d_2(Q^2)$ could be negligeable, contradicting the observation from the combined result of SLAC E155x and JLab E99-117.

The Burkhardt-Cottingham (BC) sum rule [23] is a super-convergence relation derived from a dispersion relation in which the virtual Compton helicity amplitude S_2 falls off to zero more rapidly than $\frac{1}{\nu}$ as $\nu \to \infty$. The sum rule is expressed as follows:

$$\Gamma_2(Q^2) \equiv \int_0^1 dx\ g_2(x, Q^2) = 0, \tag{6}$$

and is predicted to be valid at all Q^2. It should be noted that the validity of the sum rule has been questioned [24]. Furthermore, the BC sum rule cannot be extracted from the OPE due to the non-existent $n = 0$ expansion of g_2-moments. The data for $\Gamma_2(Q^2)$ at 5 (GeV/c)^2 from the SLAC E155x experiment showed that the BC sum rule is satisfied within a large uncertainty for deuteron. However, they found a violation of almost 3σ for the more precise proton measurement.

We separate the full $\Gamma_2(Q^2)$ integral into DIS, resonance and elastic components as follows:

$$\begin{aligned}\Gamma_2(Q^2) &= \Gamma_2^{DIS}(Q^2) + \Gamma_2^{Res}(Q^2) + \Gamma_2^{El}(Q^2) \\ &= \int_0^{x_{min}} dx\ g_2(x, Q^2) + \int_{x_{min}}^{x_\pi} dx\ g_2(x, Q^2) \\ &\quad + \int_{x_\pi}^1 dx\ g_2(x, Q^2),\end{aligned} \tag{7}$$

where, x_{min} and x_π are the x values corresponding to the invariant mass $W = 1.905$ GeV and to W at pion threshold, respectively, at the given value of Q^2. We measured the Γ_2^{Res} part in our experiment. The elastic contribution, Γ_2^{El}, was evaluated using elastic form factors from Refs. [25, 26] following the formalism of Ref. [27]. The quasi-elastic contribution to the ^{3}He BC sum rule was evaluated using the proton and neutron Γ_2^{El}; $\Gamma_2^{^3\mathrm{He},QE} = p_n \Gamma_2^{n,EL} + 2p_p\Gamma_2^{p,EL}$. This simple approximation of $\Gamma_2^{^3\mathrm{He},QE}$ was then compared to the quasi-elastic data from E94-010 to determine the "nuclear effect" correction.

There is no experimental data currently available to evaluate Γ_2^{DIS} in the Q^2 range covered by our experiment. Therefore, it is not possible to evaluate the full $\Gamma_2(Q^2)$ integral to test the BC sum rule without assumptions. Previously, JLab Hall A experiment E94-010 evaluated the BC sum rule, using the Γ_2^{WW} part for the unmeasured DIS region, at six Q^2 values from 0.1 to 0.9 (GeV/c)^2. The same method was used here: Γ_2^{WW} is calculated using our g_1 data [11]. Figure 3 shows Γ_2^{Res} and the BC sum rule for ^{3}He and the neutron compared

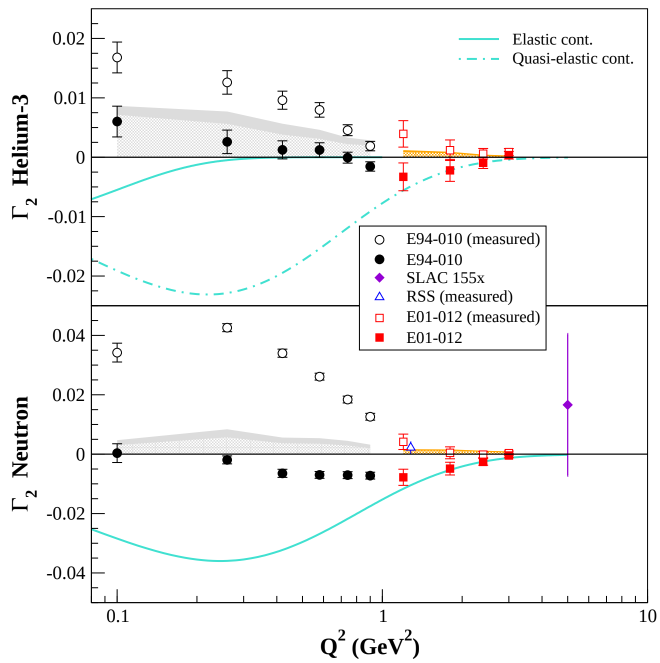


FIG. 3: (color online). The ^{3}He (top panel) and neutron (bottom panel) Γ_2 integrals from JLab E01-012 (filled squares). The error bars are statistical only, the upper band represents the experimental systematics and the lower band the uncertainties on the unmeasured part of the sum rule. The open square data are the measured part of the integral as was performed by experiment E01-012. Also plotted are data from JLab experiments E94-010 [16] and RSS [17], with also the measured part of the integral represented by open symbols and the sum rule with filled symbols, and SLAC experiment E155x [19]. The elastic (solid line) and quasi-elastic (dashed line) contributions to the integrals are plotted.

to the same quantities from the previous experiments E94-010 [16] and RSS [17]. It should be noted that RSS extracted their neutron result from the deuteron and the agreement with our data is remarkable, taking into account the difference in the nuclear corrections for deuterium and ^{3}He. All results are in good agreement with the BC sum rule for ^{3}He but indicate a deviation at the 2-3 sigma level from the neutron BC sum rule for Q^2 values between 0.5 and 1.2 (GeV/c)^2, as shown on the bottom panel of Fig. 3. This is not surprising since no higher-twist contribution from the DIS region was included in that evaluation of the sum rule. At the relatively low Q^2 values, we can expect the higher-twist contribution to Γ_2 to be important. Assuming the BC sum rule is valid, the small deviation indicates that there are higher twist effects.

In summary, we have evaluated the resonance contribution to the neutron $d_2(Q^2)$ matrix element and the ^{3}He and neutron Γ_2 moments over the Q^2 range of 1.2 to 3.0 (GeV/c)^2. Our data show both moments to be small and to gradually decrease with Q^2. The BC sum rule for ^{3}He and the neutron was also extracted from our data in the resonance region and using g_2^{WW} for the low x unmeasured part of the integral. A deviation from the validity of the BC sum rule is observed from the precise data for Q^2 values between 0.5 and 1.2 (GeV/c)^2.

We would like to acknowledge the outstanding support from the Jefferson Lab Hall A technical staff. This work supported by the NSF and DOE, including contract DE-AC02-06CH11357 and contract DE-AC05-06OR23177 under which JSA, LLC operates JLab.

[1] S. Kuhn, J.-P. Chen, and E. Leader, Prog. Part. Nucl. Phys. **63**, 1 (2009), 0812.3535.

[2] J. Chen, Int. J. Mod. Phys. **E19**, 1893 (2010), 1001.3898.

[3] K. G. Wilson, Phys. Rev. **179**, 1499 (1969).

[4] J. Kodaira, S. Matsuda, K. Sasaki, and T. Uematsu, Nucl. Phys. **B159**, 99 (1979).

[5] K. Kramer et al., Phys. Rev. Lett. **95**, 142002 (2005), nucl-ex/0506005.

[6] X. Zheng et al., Phys. Rev. Lett. **92**, 012004 (2004); Phys. Rev. **C70**, 065207 (2004).

[7] J. Blumlein and H. Bottcher, Nucl. Phys. **B636**, 225 (2002).

[8] M. Gluck, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. **D63**, 094005 (2001).

[9] M. Hirai, S. Kumano, and N. Saito (Asymmetry Analysis), Phys. Rev. **D69**, 054021 (2004), hep-ph/0312112.

[10] E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. **D73**, 034023 (2006), hep-ph/0512114.

[11] P. Solvignon et al. (Jefferson Lab E01-012), Phys. Rev. Lett. **101**, 182502 (2008), 0803.3845.

[12] A. V. Sidorov and D. B. Stamenov, Mod. Phys. Lett. **A21**, 1991 (2006).

[13] C. Ciofi degli Atti and S. Scopetta, Phys. Lett. **B404**, 223 (1997).

[14] J. L. Friar et al., Phys. Rev. **C42**, 2310 (1990).

[15] P. E. Bosted et al. (CLAS), Phys. Rev. **C75**, 035203 (2007).

[16] M. Amerian et al., Phys. Rev. Lett. **89**, 242301 (2002); Phys. Rev. Lett. **92**, 022301 (2004); Phys. Rev. Lett. **93**, 152301 (2004); Z.-E. Meziani et al., Phys. Lett. **B 613**, 148 (2005); K. Slifer et al, Phys. Rev. Lett. **101**, 022303 (2008).

[17] K. Slifer et al. (Resonance Spin Structure Collaboration), Phys. Rev. Lett. **105**, 101601 (2010), 0812.0031.

[18] D. Drechsel, S. S. Kamalov, and L. Tiator, Eur. Phys. J. **A34**, 69 (2007), 0710.0306.

[19] P. L. Anthony et al. (E155), Phys. Lett. **B553**, 18 (2003), hep-ex/0204028.

[20] M. Gockeler et al., Phys. Rev. **D63**, 074506 (2001), hep-lat/0011091.

[21] E. V. Shuryak and A. Vainshtein, Nucl. Phys. **B201**, 141 (1982).

[22] M. Gockeler, R. Horsley, D. Pleiter, P. E. Rakow, A. Schafer, et al., Phys. Rev. **D72**, 054507 (2005), hep-lat/0506017.

[23] H. Burkhardt and W. N. Cottingham, Annals Phys. **56**, 453 (1970).

[24] R. L. Jaffe, Comments Nucl. Part. Phys. **19**, 239 (1990).

[25] J. Arrington, W. Melnitchouk, and J. Tjon, Phys. Rev. **C76**, 035205 (2007), 0707.1861.

[26] R. Bradford, A. Bodek, H. S. Budd, and J. Arrington, Nucl. Phys. Proc. Suppl. **159**, 127 (2006), hep-ex/0602017.

[27] X.-D. Ji and W. Melnitchouk, Phys. Rev. **D56**, 1 (1997), hep-ph/9703363.